Future NASA Spaceborne SAR Missions

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ABSTRACT

Two Earth-orbiting radar missions are planned for the near future by NASA –Shuttle Radar Topography Mission (SRTM) and LightSAR. The SRTM will fly aboard the Shuttle using interferometric synthetic aperture radar (IFSAR) to provide a global digital elevation map. SRTM is jointly sponsored by NASA and the National Imagery and Mapping Agency (NIMA). The LightSAR will utilize emerging technology to reduce mass and life-cycle costs for a mission to acquire SAR data for Earth science and civilian applications and to establish commercial utility. LightSAR is sponsored by NASA and industry partners.

The use of IFSAR to measure elevation is one of the most powerful and practical applications of radar. A properly equipped spaceborne IFSAR system can produce a highly accurate global digital elevation map, including cloud-covered areas, in significantly less time and at significantly lower cost than other systems. For accurate topography over a large area, the interferometric measurements can be performed simultaneously in physically separate receive systems. The Spaceborne Imaging Radar C (SIR-C), successfully flown twice in 1994 aboard the Space Shuttle Endeavour, offers a unique opportunity for global multifrequency elevation mapping by the year 2000. The addition of a C-band receive antenna of approximately 60 m length, extended from the Shuttle bay on a mast, and operating in concert with the existing SIR-C antenna, produces an interferometric pair. It is estimated that the 90 percent linear absolute elevation error achievable is less that 16 meters for elevation postings of 30 meters. The SRTM will be the first single-pass spaceborne IFSAR instrument and will produce a near-global high-resolution digital topography data set.

Since LightSAR offers important benefits to both the science community and U.S. industry, an innovative government-industry teaming approach is being explored, with industry sharing the cost of developing LightSAR in return for commercial rights to its data and operational responsibility. LightSAR will enable mapping of surface change. The instrument's high-resolution mapping, along with its quad polarization, dual polarization, interferometric and ScanSAR modes will enable continuous monitoring of natural hazards, Earth's surface deformation, surface vegetation change, and ocean mesoscale features to provide commercially viable and scientifically valuable data products. Advanced microelectronics and lightweight materials will increase LightSAR's functionality without increasing the mass. Dual frequency L/X-band designs have been examined.

Keywords: Radar, interferometry, topography, vegetation, remote sensing, ScanSAR, synthetic-aperture.

1. SRTM INTRODUCTION AND REQUIREMENTS

The SIR-C/X-SAR system was a three-frequency synthetic-aperture radar system operating at L, C, and X bands that was flown on two 10-day Shuttle flights in April 1994 and October 1994.[1,2] The L-band and C-band systems employ active distributed phased-array antennas with a high degree of agility. During these same missions, they demonstrated the ability to acquire wide-swath radar images using the ScanSAR mode of operation. ScanSAR is a radar technique that allows acquisition of a larger radar swath than would normally be possible due to range-Doppler ambiguity limitations at the expense of reduced resolution. The SRTM system employs this technique with two simultaneous polarizations, each looking at a different area of the Earth at the same time. This is illustrated in Fig. 1. Also, during the last three days of the previous mission, the Shuttle was programmed to fly nearly identical orbits, which allowed the acquisition of interferometric radar data. The result of these repeat-pass interferometric data takes was a demonstration of the capability to generate topographic maps from Earth orbit with a radar system. Fig. 2 shows a topographic map generated from two separate imaging radar passes over Long Valley, California. In this topographic map, areas of equal elevation are shown in the same intensity. The outcome of these demonstrated capabilities—ScanSAR and the derivation of topography from the interferometry process—led to the design of a radar topography mapper based on the SIR-C/X-SAR system.

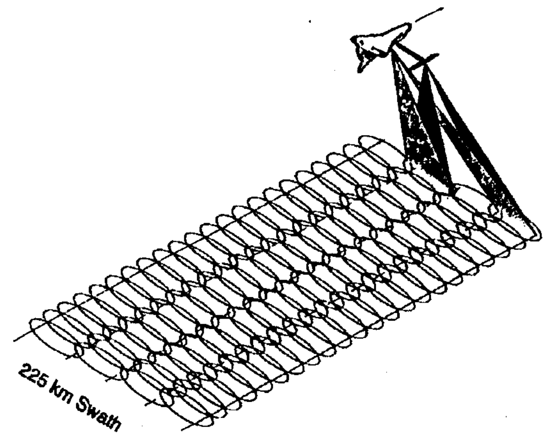


Fig. 1. Double SCANSAR data acquisition

Fig. 2. Topographic map of Long Valley, California, generated by SIR-C.

The objective of SRTM is to acquire a topographic map of as much of the Earth's surface as is feasible within the Shuttle's resources, which translates to all the land mass between the latitudes of 54° S and 60° N over a 10-day period in a 57° orbit. The topographic data set produced by this mission will satisfy requirements published in the NIMA digital terrain elevation data level 2 (DTED-2). This requirement calls for a 90 percent vertical height accuracy of 10 m relative, over a scene, and 16 m absolute, with a posting spacing of 30 m. The Shuttle is capable of supporting a 10 day mission while providing the consumables required by the SIR-C system on a 57° inclination orbit. With a 10-day repeat orbit, the required swath width for complete Earth coverage is 218 km. Due to the antenna dimensions, the only way to attain this swath width is to use ScanSAR techniques. In addition, due to the accuracy requirements, both polarizations must be used simultaneously, each acquiring data from a different area on the ground in order to provide enough simultaneous looks. Over the 159 orbits of data acquisition, a total of 80 hours of data will be acquired. After data acquisition, the topographic maps will be produced over a one-year interval at a data processing center at JPL.

1.1 SIR-C/X-SAR system description

The SIR-C/X-SAR system consists of an antenna structure supporting the three antenna arrays and the SIR-C/X-SAR electronics in the payload bay. The antenna structure occupies most of the Shuttle payload bay, with the digital routing electronics and data recorders located in the crew compartment. The SIR-C system operated at L and C bands, and each frequency used a dual-polarized distributed phased-array antenna capable of electronic steering in both elevation (cross track) and azimuth (along track). The X-SAR operated at X-band with a single polarization and was mechanically steered in elevation. The SRTM interferometer system uses the C-band portion of SIR-C, and the description that follows will concentrate on this system. In addition to the ability to electronically steer the beam, the phased-array antenna can introduce a phase function that will spoil the beamforming of the antenna and generate a beam that is wider than the ideal antenna pattern. This is a useful feature when it is desired to illuminate a larger portion of the Earth's surface than a fully focused antenna would. The nominal system characteristics of the C-band and X-band systems for the interferometer mode are listed in Table 1.

1.2 Interferometer requirements

The requirements for producing topographic data from an interferometer pair are well known and documented extensively in the literature.[3-6] In order to reduce both shadowing and layover, two well-known phenomena in SAR imaging, the local angle of incidence must be centered around 45°. In areas of shadow, it is not possible to unwrap the signal phase to derive local relative height, since signals are not present. In areas of layover, those areas where the local topography slope equals or exceeds the radar incidence angle, it is also not possible to unwrap the phase to derive relative elevation between picture elements. Combining data from both ascending and descending passes, during which the same terrains would be imaged at two different perspectives, will mitigate the amount of unresolvable data due to the effect of shadowing and layover. The local incidence angle between the radar wave and flat terrain for the SRTM is limited to those angles between 32° and 58°. To acquire interferometer SAR data for the SRTM to the required height accuracy, it is necessary to have an antenna separation, or baseline, of greater than 50 m. The baseline attitude is at an angle of 45° from the local nadir direction and must be known to an accuracy of 9 arcsec or better. The length of the baseline must also be known to an accuracy of 3 mm or better. The baseline separation and baseline attitude must be known continuously during mapping operations, since this information is required by the data processor for the calculation of absolute altitude from the center of the Earth. The Shuttle position accuracy at all times must be known to within 10 m in the horizontal plane and 1 m in the vertical plane.

Table 1. SIR-C System Characteristics for SRTM.

Parameter	Requirements
Frequency	C-Band
Polarization	Horizontal and vertical
Total Swath Width	218 km
ScanSAR simultaneous beams	Two (for each polarization)
ScanSAR beams per polarization	Two
Spatial Resolution	30 m
Bandwidth	10 MHz
System Noise Equivalent Sigma Zero	−35 dB
Transmit Power	1200 W per polarization
Main Antenna	0.74 m by 12 m
Outboard Antenna	0.74 m by 8 m
Baseline	62 m at a 45° angle from vertical
Transmit Pulse Duration	34 μs
Data Rate	180 Mbps (4 channels combined)
Final Product Resolution	30 by 30 m

3. SYSTEM DESCRIPTION

The SIR-C C-band system will remain nearly unchanged from the previous two flights, except for some modifications to adapt the existing hardware to the interferometric mission. Since the interferometer will operate as a single-pass fixed-baseline instrument, a second set of receive-only antennas, one at C band and the other at X band, will be added to the equipment complement. The new antennas will be mounted on an independent support structure, which will be stowed during launch and landing and deployed via an extendable mast while on orbit.

Figure 3 shows the on-orbit configuration. The sizes of the outboard antennas were chosen not only to satisfy the performance requirements of the interferometer, but also to take into account the available space within the Shuttle cargo bay. The mast, which provides the baseline separation between the main and outboard antennas, is contained in a 1.4-by-3-m cylindrical canister when stowed and it deploys to 60 m when fully extended. It is an actively driven mast, composed of graphite epoxy in combination with metallic end fittings, which has the advantage of being fully rigid and mechanically stable during deployment.

The outboard C-band antenna array will be based on the same dual-polarized design as the main antenna. The elevation aperture is formed by 18 elements, while the azimuth aperture will be divided into 12 subapertures. Each panel will contain low-noise amplifiers (LNAs) and phase shifters for horizontal and vertical polarization. This semiactive (receive-only) configuration will provide not only the electronically steerable beam needed for ScanSAR, it will make more effective use of the sensitivity of LNAs. On-board calibration loops will be implemented for the C-band radar to allow monitoring system stability, in particular to meet the stringent phase stability requirement.

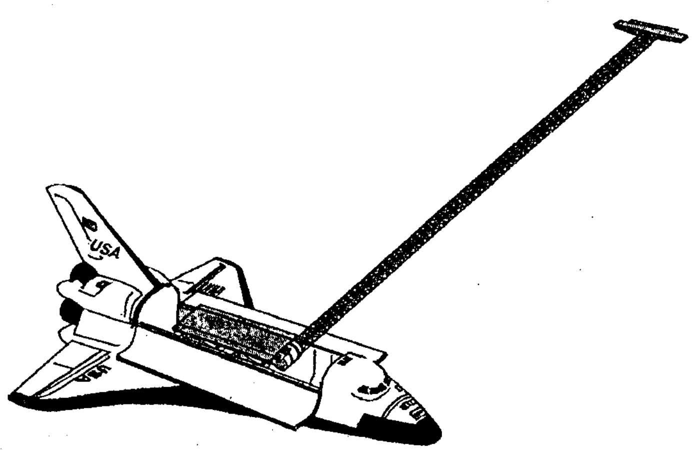


Fig. 3. SRTM interferometer configuration

3.1 Metrology

The metrology subsystem has three functions. The first is to measure the characteristics of the interferometer baseline to a high accuracy. The second is to calculate the position of the Shuttle. The third is to provide the interferometer system with a precise time base to which all measurements can be related. The absolute baseline attitude is measured with a combination of sensors. The first is a star tracker mounted on an optical bench at the base of the main antenna. The star tracker provides absolute attitude updates to an inertial reference unit. A second tracker, looking out from inboard to outboard, will detect and monitor the relative motion of the outboard antenna with respect to the inboard mounting platform by observing three light sources (LEDs) mounted on the outboard antenna. Electronic distance meters will provide direct distance measurements between the platform a corner cube on the outboard antenna and the X-band main antenna. The absolute position of the Shuttle is measured by the Global Positioning System (GPS), which uses an antenna mounted on the outboard antenna structure. The GPS also provides the common time base to which all measurements are tied. While the data acquired by the metrology system will aid on-orbit checkout alignment, it will be processed post-mission to provide precision attitude and position of the radar instruments throughout the mission. The processed products are critical for height processing.

3.2 Onboard data handling and storage

The raw radar signals from four SIR-C receiver channels, two channels (HH and VV) each from primary and outboard antennas, are digitized into four 8-bit data channels, which also compress the 8-bit data into 4-bit with each channel having an output rate of 45 Mbits/s. The four data channels are multiplexed into a single 180-Mbit/s data stream to be recorded by one of the three payload high-rate recorders (PHRR). Written at 180 Mbits/s (SIR-C multiplexed data rate), the digital tape cassette for the PHRR can record up to 30 minutes on a single cassette, or about 300 Gbits (about 40 Gbytes) per cassette. The raw radar data, called high rate data, can be simultaneously routed with multi-channel playback data, to the ground during the mission via the Telecommunications and Data Relay Satellite System (TDRSS) link.

3.3 Data processor and topographic map generation

After the end of the mission, the digital tapes will be duplicated, and the data tapes will be sent to their respective ground data processing centers. The processing procedure to generate the topographic maps is basically as follows. First, the radar data from each of the two interferometric channels is processed to generate phase maps. A difference phase map is then produced for an entire pass between ocean coastal crossings. Using the baseline angle and length information from the metrology system, a relative height map is then obtained from a phase unwrapping algorithm. The absolute height maps are then generated after calculation of the ocean heights derived from ocean models and tide tables provided by the TOPEX/Poseidon project. There are also plans to perform calibration and validation during and after the mission using a combination of, in addition to the ocean models, ground control points and GPS survey.

4. SRTM CONCLUSIONS

The Shuttle Radar Topography Mission is the first of its kind to exploit the radar interferometry technique to acquire topographic maps on a global scale with unprecedented overall spatial resolution, height accuracy, and data uniformity. Using modified existing and flight-proven SIR-C/X-SAR hardware, the mission represents the most cost-effective means to acquire such a global map in the shortest time possible. Unlike the repeat-pass interferometry, which was tested successfully during the previous SIR-C/X-SAR mission and is currently being performed by existing spaceborne SAR systems such as ERS1/ERS2 tandem data and RadarSAT data, the fixed-baseline SRTM system provides the most stable configuration for calibrated interferometry data acquisition. Temporal decorrelation, uncertainties in baseline, tropospheric disturbance, among others, tend to affect the height accuracy attainable by repeat pass approach; whereas these factors are literally none existent for fixed baseline systems such as SRTM.

5. LIGHTSAR INTRODUCTION AND REQUIREMENTS

This is a technical summary of the LightSAR system design studies performed by JPL. LightSAR is a NASA initiative to develop a low-cost Earth-imaging radar satellite system that will return valuable science data, demonstrate advanced technologies, and revolutionize commercial radar imaging from space. Unlike SRTM's 10-day mission LightSAR is planned for 3-5 yr.

Because LightSAR offers important benefits both to the science and civil operations community and to U.S. industry, an innovative government-industry teaming approach is being explored, with industry sharing the cost of developing a LightSAR mission in return for commercial rights to its data and operational responsibility. The four industry teams selected to work on LightSAR definition studies are reviewing business and teaming approaches, preparing market analyses, developing applications, defining technical approaches, and identifying potential industry cost-sharing of follow-on development. This approach is also gathering experience from previous commercial space-based imaging radar efforts.[7]

The LightSAR designs presented here are non-optimized engineering solutions, formulated as a costed-design, which has been examined in sufficient depth to establish confidence that it can be produced and will meet a broad set of science requirements. The LightSAR designs achieve reduced costs by using advanced radar technology components with a proven commercial spacecraft bus, by using commercial launch and operations services, and by following a lean, fast-paced schedule. Conclusions from the LightSAR design exercise are: (1) LightSAR is technically feasible, and (2) LightSAR costs can be reduced to 25 percent of those of any previous free-flying, space-based imaging radar (including launch services).

Because of its planned long-term (3-5 yr) operation, LightSAR would collect large amounts of information about our changing planet. It would provide an important contribution to NASA's Mission To Planet Earth (MTPE) program and to civilian environmental operational monitoring programs.[8] This project is a long-term research effort designed to provide better understanding of how the Earth is changing, how human activities cause or contribute to these changes, and how the changes affect us. In addition, the information from LightSAR could potentially help us address a range of issues.

One example would be measuring motion of the Earth's surface to help to better understand earthquakes and volcanoes and to support emergency management efforts. Other possibilities include studying the movements and changing size of glaciers and ice floes to better understand long-term climate variability; developing highly detailed and accurate elevation maps; monitoring floods and predicting where they are likely to occur; assessing terrain for the likelihood of discovering oil or other natural resources; early recognition and monitoring of oil spills; assessing the health of crops and forests; planning urban development and understanding its likely effects; studying land cover and land-use change. Because of advances in radar and spacecraft technology, the LightSAR spacecraft under study would be much smaller and less expensive and provide greater capability than comparable systems that are now in orbit.

The LightSAR satellite would provide nearly complete coverage of the Earth's surface every 8-10 days. This repeating coverage would give LightSAR the unique capability of continuously monitoring changes in the Earth's topography as small as a few millimeters. Capabilities under study would enable the radar to measure features as small as 1-3 meters, offering significant potential for commercial use in topographic mapping, land management, planning, and development.

6. MISSION DESCRIPTION

LightSAR will generate data for commercial, Earth science, and civilian applications. It will allow mapping of surface change, because its repeat-pass interferometry technique will enable continuous monitoring of Earth's dynamic topography to a height accuracy of a few millimeters. Moreover, LightSAR will have the ability to map large areas of the surface of the Earth, especially oceans, using the ScanSAR technique described for the SRTM mission. To provide both high-resolution measurements for commercial interests and large-scale geophysical measurements a dual frequency (L- and X-band) configuration was investigated as well as a single frequency (L-band) configuration. Because of federal regulations restricting the bandwidth available at L band, resolution greater than 3 m is not realizable.

6.1. Radar design

A parameterization of the L-band and X-band radar designs considered is presented in Table 2. Note that the table shows not only the frequency diversity but the polarization and operational mode diversity as well.

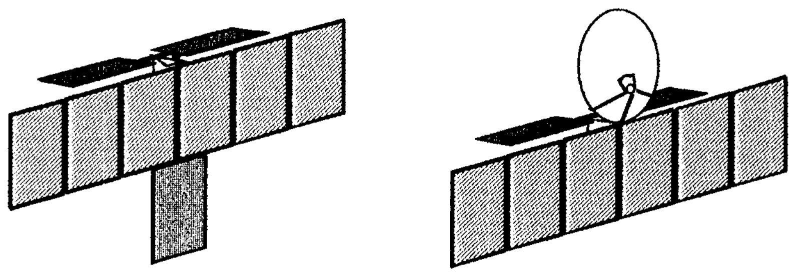
The longer (L-band) wavelength radar and use of multiple polarization modes will allow better distinction of textures, vegetation structures and water content, soil moisture, ice thickness, and other parameters.
Imaging swaths 100 km wide will provide 25-m horizontal resolution, accurate to within a few millimeters vertically. As shown in Table 2, even higher resolution, 1-3 meters, is being considered in order to provide opportunities for additional commercial applications, such as high-resolution surface mapping and co-registration with electro-optical sensor data. The wide-swath (280 km) ScanSAR mode will provide large-area mapping over the 500-km-wide access area.

Table 2. LightSAR Dual Frequency Design Comparison.

Operational Mode:	HiresX	HiresL	Repeat-pass I/F	Quad-pol	Dual-pol	ScanSAR
Frequency	X-Band	L-Band	L-Band	L-Band	L-Band	L-Band
Resolution (m)	1	3 or 5	40	25	25	100
Swath (km)	10	10	90	30, 60	50	280
Looks	2	1-2	8-16	3-4	8	8
Quantization	(8, 2) BFPQ	(8, 4) BFPQ	(8, 4) BFPQ	(8, 4) BFPQ	(8, 4) BFPQ	(8, 4) BFPQ
Incidence Angle	25 - 45°	25 - 45°	25 - 45°	20 - 40°	25 - 52°	20 - 52°
Polarizations	HH	HH or HH + VV	HH or VV	HH, HV, VH, VV	HH, HV or VV, VH	HH, HV
PRF (Hz)	12308-16166	2576-4143	1589-1916	3043-3547	1986-2641	1164-2000
Pulse Length (ms)	15	10	15	3	10	2.8-15
Average RF Power (W)	15-1900	210-330	190-230	73-80	160-210	30-130
Data Rate (Mbps)	9-1100	98-163	72-88	101-163	93-113	21-40

Characteristics of LightSAR design concepts under study include state-of-the-art technologies with significant reduction in mass and volume, as well as instrument and mission life-cycle costs. These technologies, such as monolithic microwave integrated circuits (MMIC), when applied to an L-band, multipolarization, high-performance SAR with multiple resolutions and swath imaging capabilities will increase the radar capability without increasing the mass. To meet the imaging agility needs, electronic beam steering has been considered in order to maximize the targetable swath. In addition, as noted previously, X band is being considered for very high-resolution commercial applications, although, C band also has sufficient bandwidth allocated to meet high-resolution imaging needs. Figure 4 illustrates two configurations for a dual-frequency system concept.

To make LightSAR commercially viable and to obtain time series of data over multiple seasons, designs for missions with lifetimes of 3-5 years are being examined. The design life is important in terms of the reliability of the electronics, and there are cost implications to both selective and the sizing of propellant required to maintain the orbit over the mission life. Additional electronics and propellant translate into additional mass, which results in higher costs for more capable launch vehicles. Therefore, a delicate balance must be achieved between the overall system performance and the scope of requirements.



X-Band options:
- Passive Antenna (Elliptical Reflector) or Active Antenna (Phased Array)
- Left- or Right-looking (mechanical)
- Single or dual-redundant TWT Amplifier (s) for reflector solution
- ~1000 x 8 Watt T/R modules (Phased Array)
- Single polarization (HH or VV)
- Single mode operation (Strip map)

Antenna Size:	1.35 (1.8) x2.9m
Peak Power:	8 kW
Pulse Length:	15 µs
Bandwidth:	300 MHz
PRF:	15000 Hz
Illuminated Swath:	10 km
Resolution:	1m x 1m
Number of looks:	2
Instantaneous Data Rate:	1200 MBps

L-Band system:
- Active Antenna (electronic steering)
- Left- or Right-looking (mechanical)
- Distributed phased array (T/R modules)
- Multi-polarization capability
- Multi-mode capability (Spotlight, ScanSAR, Quad- or dual-pol, Repeat-pass I/F)

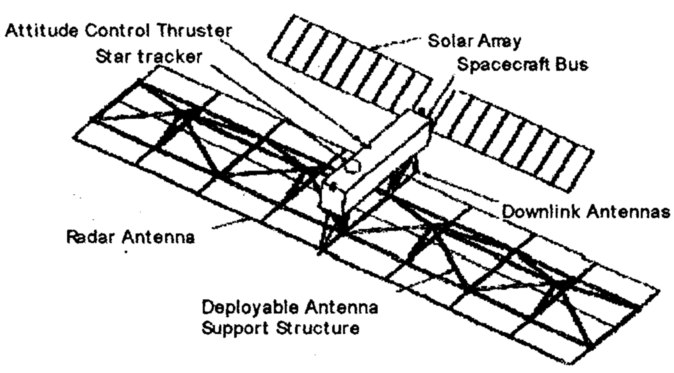
Antenna Size:	10.8 x 2.9m
Peak Power:	8 kW
Pulse Length:	15 µs
Bandwidth:	80 MHz
PRF:	1600 Hz
Illuminated Swath:	20 km
Resolution:	3m x 3m
Number of looks:	2
Instantaneous Data Rate:	150 MBps

Figure 4. System configurations and designs for an L/X-band mission.

6.2. Orbit considerations

LightSAR's eight to 10-day repeating orbit maintained within a 250-m-diameter tube (determined by GPS), would provide visibility of most locations on Earth about once each day. The repeat period was defined to meet imaging requirements for glacier research. Flying within a 250-m tube is a significant requirement that must be met in order to achieve global surface deformation measurements, with accuracies of a few millimeters, using repeat pass interferometry. For design purposes a sun-synchronous orbit at an altitude of 600 km, with an inclination of 97.8°, was evaluated. Orbits at lower inclinations were also examined. Moreover, the orbit must be known with an accuracy of <10 cm radially and cross-track and 1 m along-track. State-of-the-art GPS precision orbit determination techniques pioneered by JPL are capable of obtaining this orbit knowledge. Commercial requirements for the orbit control and precise orbit determination are less stringent.

Figure 5. LightSAR Mechanical Configuration (L band only).



6.2. Spacecraft Bus

Several aerospace companies have low-cost spacecraft bus designs that could serve as the LightSAR bus. Bus adaptations required to accommodate the radar instrument(s) include: attachment of the radar antenna, deployment structure, and latch mechanism; installation of radar electronics in the bus; provision for unique memory and data handling capacity; tailored downlink transmitter(s)/antenna(s); tailored solar array and battery provisions; tailored attitude control provisions; and tailored GPS configuration. Figure 5 illustrates the mechanical configuration for LightSAR with an L-band radar only. The bus configuration shown is generic and is used for design and cost evaluation purposes to convey one of many possible designs.

Table 3 summarizes the performance needed for a bus to support an L-band radar mission. The addition of a second radar will require evaluation of the mechanical configuration and deployment mechanisms as well as the power demands, as shown in Table 2, for X-band. The current LightSAR design requires that the bus be capable of rolling 70° (±35° from nadir) to perform high-latitude mapping near the poles (up to 80° N and 86° S). This capability also is required in order to provide maximum coverage and responsiveness to commercial imaging customers.

Table 3. LightSAR Bus Performance for an L-band Radar.

Feature	Capability
Autonomy	Operate w/o commands 24 hr (typical), 7-day max
Mass	<710 kg (flight weight, without single frequency 250 kg radar, including 30% contingency)
Power	50 Amp-Hr batteries; 1-axis gimbaled solar array
Attitude Control	Pointing Accuracy: elevation 0.5°, azimuth 0.1°; knowledge: 0.01° Perform 70 degree roll in 10 min. (for right and left looking)
Propulsion	Maintain 250-m-diam. tube about the velocity vector
Data Storage	90-Gbit solid-state recorder, radar data recording for ~1 orbit (Spotlight mode), > 3 orbits (ScanSAR mode)
Command/Telemetry	S-band receiver/transmitter, with command encryption
Data Link	Radar: X-band transmitter, at 160 Mbps (L-band radar, only)
Subsystems	Assumed design includes hot gas thrusters, reaction wheels, inertial reference unit(s), star tracker(s), sun sensors, magnetometer, and onboard (GPS)

7. LIGHTSAR CONCLUSION

LightSAR is the first NASA commercial SAR mission. An innovative NASA-industry partnership has been established to reduce the cost of the SAR mission by a factor of four while increasing the capability. This partnership will utilize advanced MMIC devices and lightweight materials to develop a high-performance radar system that will meet both NASA's science goals and industry's commercialization goals. A new set of working relationships and technologies will be applied, and existing spacecraft, launch vehicles and an operations infrastructure will be used to reduce costs and maintain a schedule that will bring LightSAR to orbit years sooner than was previously achievable.

8. ACKNOWLEDGMENTS

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